The Revised Orbit of the δ Sco System

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ABSTRACT

In anticipation of the possible collision between a circumstellar disk and the secondary star in the highly eccentric binary system δ Scorpii, high angular resolution interferometric observations have been acquired aimed at revising the binary parameters. The Navy Prototype Optical Interferometer (NPOI) was used to spatially resolve the binary components in 2000 and over a period between 2005 and 2010. The interferometric observations are used to obtain the angular separations and orientations of the two stellar components at all epochs for which data has been obtained, including 2005 and 2006, for which based on previous studies there was some uncertainty as to if the signature of binarity can be clearly detected. The results of this study represent the most complete and accurate coverage of the binary orbit of this system to date and allow for the revised timing of the upcoming periastron passage that will occur in 2011 to be obtained.

Subject headings: techniques: interferometric – stars: individual (δ Sco) – binaries: general – stars: emission-line, Be

1. Introduction

δ Scorpii (HD 143275, HR 5953, FK5 594) is a well known binary system with a highly elliptical orbit and a period of almost 11 years. The primary star is classified as a Be star with a gaseous circumstellar disk and the secondary is a B2-type star (Tango et al. 2009). This system has been a subject of a number of studies that investigated a range of different characteristics ranging from the disk structure around the primary (Carciofi et al. 2006;

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In anticipation of the possible collision between a circumstellar disk and the secondary star in the highly eccentric binary system   Scorpii, high angular res- olution interferometric observations have been acquired aimed at revising the binary parameters. The Navy Prototype Optical Interferometer (NPOI) was used to spatially resolve the binary components in 2000 and over a period be- tween 2005 and 2010. The interferometric observations are used to obtain the angular separations and orientations of the two stellar components at all epochs for which data has been obtained, including 2005 and 2006, for which based on previous studies there was some uncertainty as to if the signature of binarity can be clearly detected. The results of this study represent the most complete and accurate coverage of the binary orbit of this system to date and allow for the revised timing of the upcoming periastron passage that will occur in 2011 to be obtained.

15. SUBJECT TERMS

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Halonen et al. 2008; Millan-Gabet et al. 2010) to refining the binary parameters (Bedding 1993; Hartkopf et al. 1996; Miroshnichenko et al. 2001; Mason et al. 2009; Tango et al. 2009). Because the primary did not possess strong Hα emission during the previous periastron passage in 2000, whereas as of late δ Sco has shown strong Hα emission, the high likelihood that some type of interaction between the secondary and the circumstellar disk of the primary will occur during the upcoming periastron passage in 2011 makes this system particularly interesting. Being such a high priority target for many observational campaigns scheduled for 2011 creates the need for accurate binary parameters such that the upcoming periastron passage can be predicted with high accuracy. This is especially important for the targeted observational campaigns that request a very limited number of telescope nights near the periastron passage.

The most recent binary parameters established for δ Sco were presented by Mason et al. (2009) and Tango et al. (2009). Mason et al. (2009) have revised the orbit using speckle interferometry complemented with radial velocity data from Miroshnichenko et al. (2001). Similarly, Tango et al. (2009) combined the speckle data with additional optical interferometric data from the Sydney University Stellar Interferometer (SUSI) obtained between 1999 and 2007. However, except for the observations obtained on four nights in 1999, the interferometric observations obtained with SUSI have not detected the binary signature. Tango et al. (2009) attributed this to a fully resolved circumstellar structure (with an estimated size of more than 4 mas) associated with the primary component. However, this is inconsistent with the results of Millan-Gabet et al. (2010) who based on 2007 observations estimated the size of the circumstellar disk to be in the 1 mas range (although their measurements have been obtained in the H and K band as opposed to the optical). In this study, we show how the interferometric observations obtained with the Navy Prototype Optical Interferometer (NPOI) at the same epochs clearly resolve the binary signature. Nevertheless, Tango et al. (2009) have obtained the best orbital elements published to date with a newly revised period of 10.74 ± 0.02 yr.

The high eccentricity of this system requires that the period should be known with high accuracy if the periastron passage is to be predicted with sufficiently high accuracy to be useful for targeted observational campaigns. This is because uncertainties of even a few days in this 11-year period translate to very significant motions near the periastron passage. Therefore, to assist any upcoming observational campaigns aimed at observing the δ Sco system near its periastron passage, the main focus of this study is the revision of the binary parameters. We acquired interferometric observations of the δ Sco binary system using the NPOI, which are used to obtain high precision relative astrometric positions between the stellar components. The astrometric data is then combined with the radial velocities from Miroshnichenko et al. (2001) to produce the most accurate orbital parameters for this system

to date.

2. Observations and Reductions

The interferometric data used in this study have been acquired using the NPOI on two nights in 2000 July (shortly before the last periastron passage) and with the rest obtained over 94 nights between 2005 June and 2010 August. There were about a dozen or so nights in the latter period that have not been utilized in this study since these nights produced small amounts of low quality data most commonly due to poor atmospheric conditions. Therefore, a total of 96 nights have been used where the dates of all these nights are listed in Table 1.

The NPOI is a six-element optical long-baseline interferometer that has been described in detail by Armstrong et al. (1998). The interferometric observations obtained during our δ Sco campaign have utilized all six operational stations resulting in baseline lengths from 18 to 80 m. The raw interferometric data were obtained and reduced using steps outlined in Hummel et al. (2003), Benson et al. (2003), and Koubský et al. (2010). The calibrator star used was ζ Oph (HR 6175, O9V) with an estimated diameter of 0.85 mas based on the $R - I$ color (Mozurkewich et al. 1991).

The interferometric binary signature for each individual night in our data set was modeled in the same manner as described by equation 1 in Tango et al. (2009). To estimate the squared visibility curve of the two stellar components we assumed that the two angular diameters are known. For the primary component we adopted the measured uniform disk diameter of 0.45±0.04 mas from Hanbury Brown et al. (1974). For the secondary component we adopted an angular diameter of 0.2 mas (nearly unresolved for the employed baselines), which is expected based on the average value of 5.7 $R_\odot$ from tabulations of Cox (2000) for a B2-type main sequence star and a dynamical parallax of 7.03±0.15 mas (Tango et al. 2009). Figure 1 illustrates a typical interferometric binary signature across different spectral channels of a single baseline obtained during the 2006 observing season. Because the main purpose of this study is to revise the binary parameters, we exclude from the analysis the spectral channel that contains the Hα emission from the circumstellar disk around the primary. We leave the analysis of the Hα-emitting region in the δ Sco system for future publication.

The resulting binary fits to each night produced the angular separation (ρ) and the position angle (P.A., θ) of the two stellar components, as well as their magnitude difference. The median magnitude difference between the two components based on all the nights yielded Δm values of 1.87±0.17 and 2.24±0.26 for the 550 and 850 nm regions, respectively.

This is in an agreement with the values of ≈ 1.9 (Hanbury Brown et al. 1974) and 1.78±0.03 (Tango et al. 2009), based on observations in the 440 nm region. The astrometric fits were repeated adopting the median values of the magnitude differences, and the uncertainty ellipses were adopted as one-seventh the size of a Gaussian fitted to the center of the synthesized point-spread function (Hummel et al. 2003). The astrometric results for all nights are listed in Table 1.

3. Results

3.1. Revised Binary Parameters

Following a similar procedure outlined by Hummel et al. (2003) we have combined our astrometric measurements with the radial velocities obtained by Miroshnichenko et al. (2001) during the last periastron passage that occurred in 2000. Because Miroshnichenko et al. (2001) did not publish uncertainty estimates, we adopted 1.8 km s^{-1} as the measurement error of a radial velocity based on their scatter in the final fit. The astrometric uncertainty ellipses did not have to be rescaled before combination as their size corresponded to the average deviation from the fitted positions. For the systemic radial velocity we used the value of -7 km s^{-1} from (Evans 1967). We also fixed the mass of the secondary at $8M_\odot$, the value found by Tango et al. (2009). Based on its color of $(B - V) = -0.20$ derived from the measured magnitude differences, it is likely a dwarf of type B2 for which a mass of $8M_\odot$ is listed by Cox (2000). This leaves the mass of the primary and the seven orbital elements to be fit to the combined data using standard nonlinear least-squares methods.

The combined astrometric and radial velocity data resulted in the best-fit orbital parameters listed in Table 2, where our values are also compared to the results from Miroshnichenko et al. (2001), Mason et al. (2009), and Tango et al. (2009). The reduced χ^2 statistic associated with the best-fit solution was 1.2. The mass of the primary is derived as $12.4 \pm 0.8M_\odot$, and the dynamical parallax is 7.4 ± 0.2 mas.

Figure 2 compares how well the revised model fits the actual astrometric data and compares the revised orbit to the one obtained by Tango et al. (2009). It is clearly evident from the figure that the wide range of baselines of the NPOI produces very high precision narrow-angle astrometric measurements. The high precision astrometry compounded with the extensive orbital coverage that includes observations close to the previous periastron passage, results in the best orbital parameters to date.

3.2.   Periastron Passage

Our best-fit values for T_0 and P of JY2000.6927 (JD2,451,798) and 10.817 yr (3950.9 ± 1.7 d), respectively, allow us to revise the timing of the upcoming periastron passage to UT2011 Jul 6 ± 2 d. This revised periastron timing differs by ≈ 30 days from the predictions based on the most accurate orbital parameters published to date. Because the secondary moves rapidly near periastron passage, observations acquired even a few days before or after the closest approach might miss the possible disk-secondary interaction completely. Figure 3 illustrates where the secondary is expected to be located 10, 30, and 60 days before and after the periastron passage, along with the locations of the secondary along our newly revised orbit based on the periastron timings derived based on the T_0 and P values published in the literature.

Using the updated orbital parameters we also derive the minimum expected separation at the closest approach (ρ_{min}) to be 6.14 ± 0.07 mas (14 stellar radii). The uncertainty in the separation at the closest approach was obtained using a Monte Carlo approach, which simulated 300,000 synthetic data sets all distributed according to the uncertainties associated with all the orbital parameters. By obtaining a ρ_{min} value for each synthetic data set allowed us to obtain a distribution of solutions where the standard deviation of the distribution was used to obtain the uncertainty on ρ_{min}.

4.   Summary

The binary orbit has been refined using astrometric data obtained from NPOI and radial velocities from Miroshnichenko et al. (2001). The orbit that is obtained gives a better fit to the data than previous findings. The next periastron passage is expected to occur on UT 2011 Jul 6 ± 2 d. Our results indicate that the periastron passage will occur almost one month later compared to what one would expect based on the period reported by Tango et al. (2009). This result can have a significant impact on observational campaigns that request relatively small amount of telescope time (sometimes months in advance) and need to time their request as closely to the periastron passage as possible.

Facilities: NPOI

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Table 1: NPOI Astrometric Results

UT Date	JY	ρ	θ	Error Ellipse		
				σ_{maj}	σ_{min}	ϕ
	(yr)	(mas)	(deg)	(mas)	(mas)	(deg)
2000 Jul 27	2000.5690	20.23	49.64	1.171	0.124	12.8
2000 Jul 28	2000.5718	19.62	50.68	0.963	0.113	8.5
2005 Jun 28	2005.4889	191.45	353.01	0.605	0.069	179.6
2005 Jun 29	2005.4917	191.30	352.99	0.575	0.061	175.3
2005 Jun 30	2005.4944	191.26	353.00	0.603	0.058	174.8
2005 Jul 1	2005.4971	191.15	353.01	0.556	0.065	178.4
2005 Jul 2	2005.4999	191.38	353.01	0.562	0.066	177.0
2005 Jul 3	2005.5026	191.48	353.03	0.621	0.062	175.4
2005 Jul 4	2005.5054	191.05	353.03	0.576	0.065	176.9

Notes. Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. Column 1: UT date of the observation; Column 2: Julian year; Column 3-4: separation and P.A. (north through east); Column 5: semi-major axis of error ellipse; Column 6: semi-minor axis of error ellipse; Column 7: P.A. of error ellipse

Table 2: The orbital elements for δ Sco

Orbital Parameters	Miroshnichenko et al. (2001)	Mason et al. (2009)	Tango et al. (2009)	This Work
a (mas)	107[a]	104 ± 6	98.3 ± 1.2	99.1 ± 0.1
i (deg)	38 ± 5	39 ± 8	38 ± 6	32.9 ± 0.2
Ω (deg)	175[a]	153 ± 9	175.2 ± 0.6	172.8 ± 0.9
e	0.94 ± 0.01	0.94[b]	0.9401 ± 0.0002	0.9380 ± 0.0007
ω (deg)	-1 ± 5	29 ± 12	1.9 ± 0.1	2.1 ± 1.1
T_0 (JY)	2000.693 ± 0.008	2000.693[b]	2000.69389 ± 0.00007	2000.6927 ± 0.0014
P (year)	10.58[a]	10.68 ± 0.05	10.74 ± 0.02	10.817 ± 0.005

Notes.

[a]Parameter adopted from Hartkopf et al. (1996) solution.

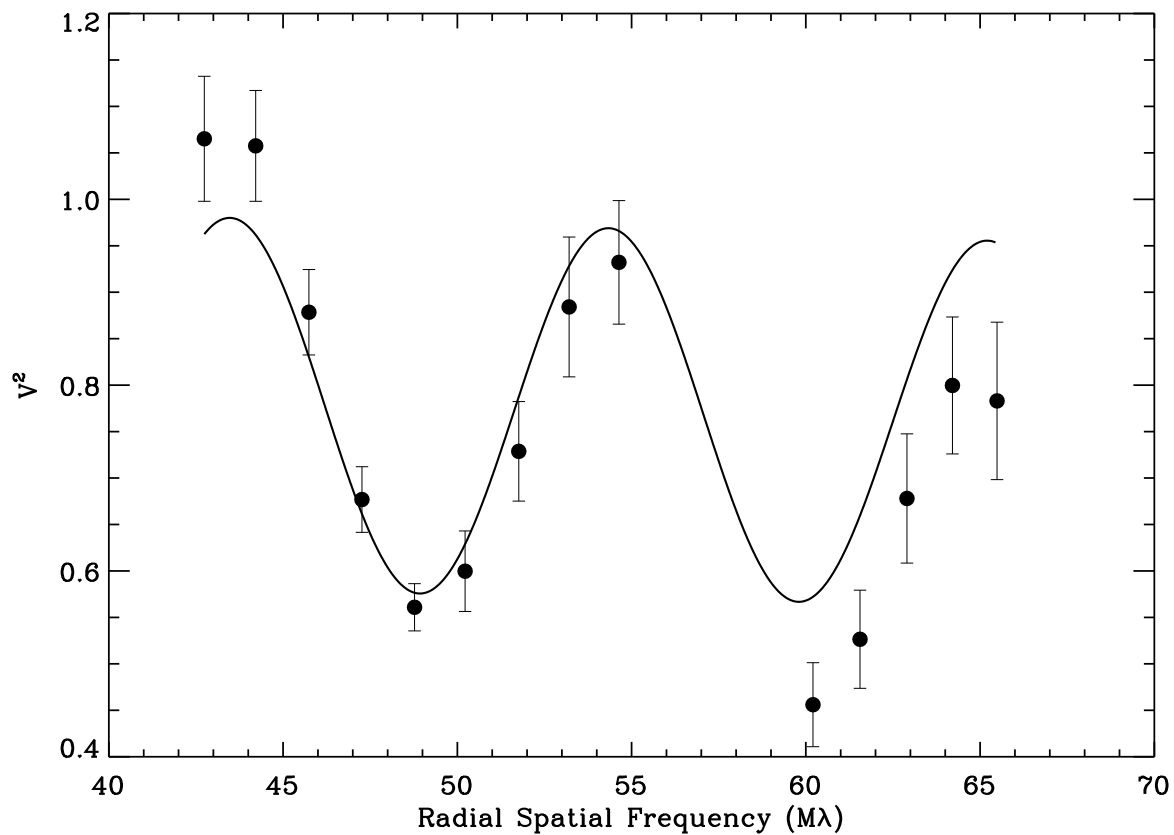[b]Parameter adopted from Miroshnichenko et al. (2001) solution.

Fig. 1.— Squared visibility data obtained for δ Sco on 2006 June 5 across 14 spectral channels plotted as a function of radial spatial frequency. Data from only one scan and one baseline are plotted for clarity to illustrate the interferometric binary signature in the form of a cosine (*solid line*) that is used to obtain the angular separation and orientation of the binary components.
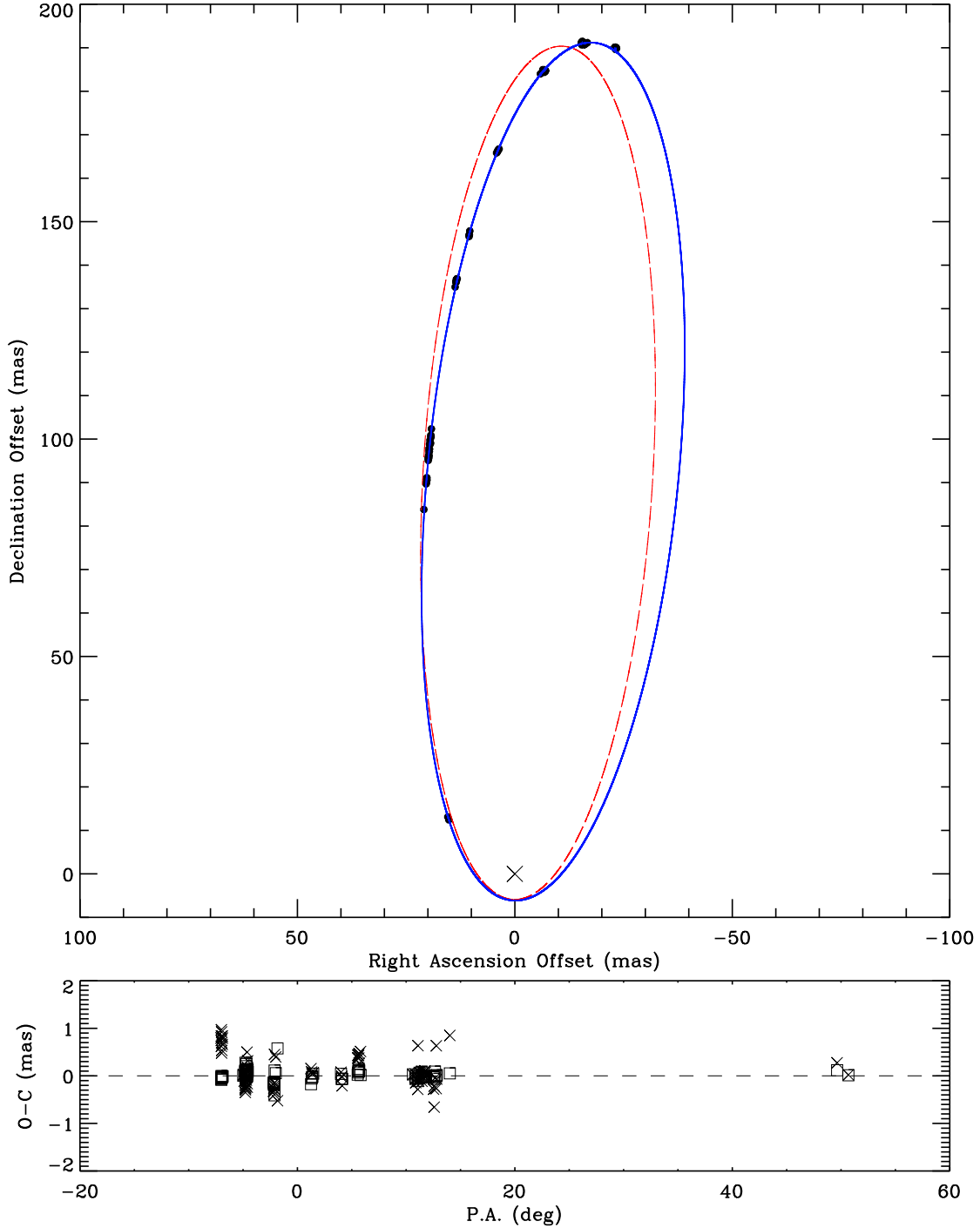
Fig. 2.— Top panel: Binary orbits based on the parameters from Table 2 based on the best-fit parameters from this study (*solid line*) and those based on Tango et al. (*dashed line*) plotted with the astrometric results (*filled circles*) of Table 1. The uncertainty ellipses of the astrometric data are generally smaller than the size of the plotted symbols and were omitted for clarity. The location of the primary is marked with an X. Bottom Panel: The east-west (*squares*) and north-south (*crosses*) components of the O–C vectors as a function of the P.A. of the secondary.
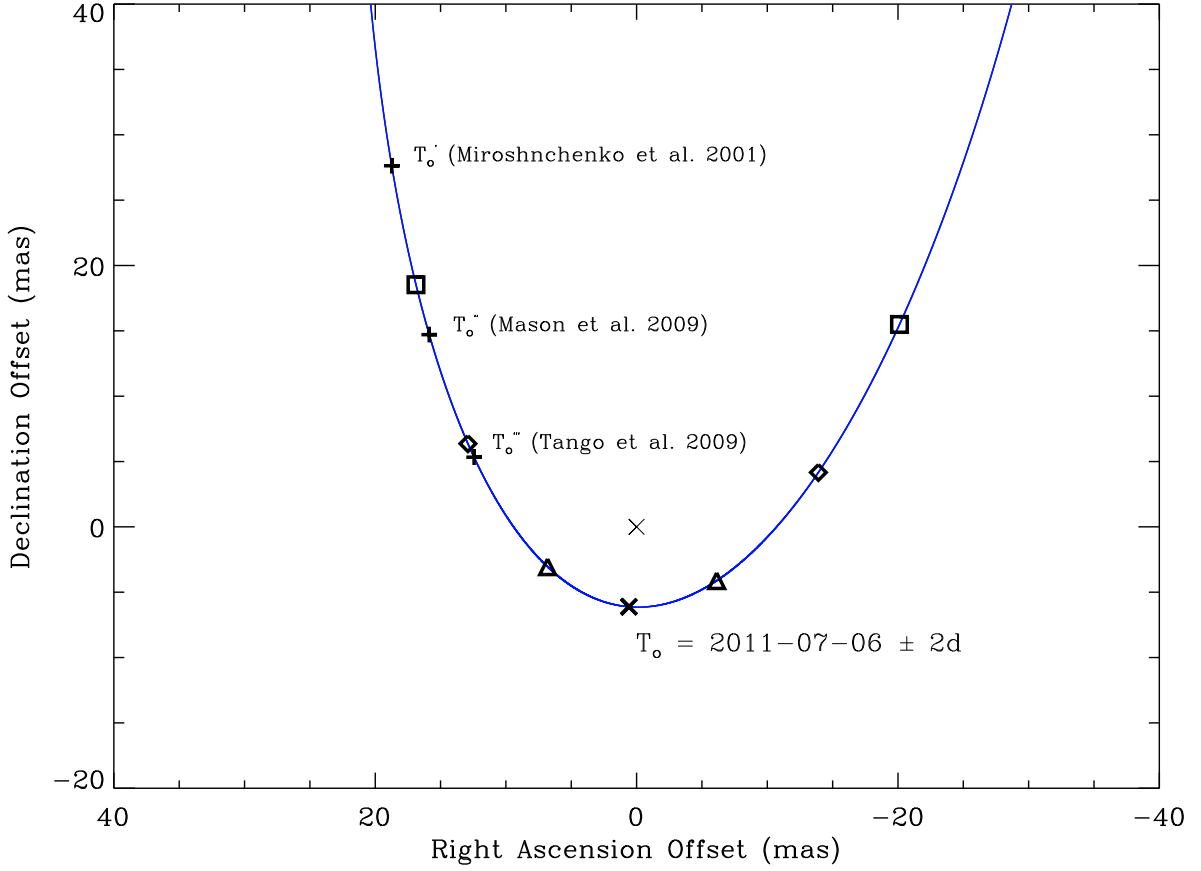
Fig. 3.— Predicted positions of the secondary during the upcoming periastron passage in 2011 at 10 days (*triangles*), 30 days (*diamonds*) and 60 days (*squares*) before and after the periastron passage (*cross*). Locations of the secondary along the newly revised orbit based on periastron timings from previous studies are also shown (*pluses*). All positions are measured with respect to the primary, which is located at the origin of the plot.